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Editor's introduction

This column continues the excellent series of articles on the geometry and comparisons of dual-reflector antennas by Christophe Granet. His earlier contributions, in 1998, provided readers with equations to determine the parameters of dual-reflector antennas, which I recommend you review and make a part of your design toolbox. I will still send you the *FORTRAN* source code for those equations, reduced to a series of subroutines, if you send me an e-mail.

It is not necessary to review his earlier articles, in 1998, because the article below stands alone. The displaced-axis reflector is a compact antenna, suitable for communication antennas. It has high efficiency and a compact geometry. Christophe provides us equations for geometries other than the one presented in 1997.

A Simple Procedure for the Design of Classical Displaced-Axis Dual-Reflector Antennas Using a Set of Geometric Parameters

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1. Abstract

A simple procedure for the design of classical displaced-axis dual-reflector antennas is given. Using four geometric input parameters, a set of equations is derived to find the remaining geometric parameters, fully defining the systems. This initial geometry provides a good starting point for any optimization process.

2. Introduction

The standard displaced-axis dual-reflector antennas are special cases of the Gregorian or Cassegrain systems, in which the focal axis of the main parabolic reflector is displaced from the axis of symmetry. The prime focus of the elliptical or hyperbolic subreflector is also located on this axis, and not on the axis of symmetry [1-4].

A dual-reflector antenna system can be described using a finite set of simple geometric parameters [5]. The geometric parameters necessary to design circularly-symmetric displaced-axis dual-reflector antennas are presented in this paper, using four input parameters. In this paper, only classical systems are presented: no special shaping of the reflectors is taken into account.

There are four options available:

- Option 1: a displaced-axis Gregorian antenna with a single offset (see Section 5.1).
- Option 2: a displaced-axis Gregorian antenna with a double offset (see Section 5.2).
- Option 3: a displaced-axis Cassegrain antenna with a single offset (see Section 6.1).

- Option 4: a displaced-axis Cassegrain antenna with a double offset (see Section 6.2).

By single offset, we mean that the distance between the bottom of the half-subreflector used and the bottom of the half-main-reflector used is of the order of $1 \times (D_s/2)$ (as in Figures 1 and 4), while for a double offset, it is of the order of $2 \times (D_s/2)$ (as in Figures 3 and 6).

3. General geometry of a displaced-axis dual-reflector antenna

In a dual-reflector configuration, it is customary to define the main reflector and subreflector in their own coordinate systems, $(O_{MR}, X_{MR}, Y_{MR}, Z_{MR})$ and $(O_{SR}, X_{SR}, Y_{SR}, Z_{SR})$, respectively, and to have a general antenna coordinate system (G, X, Y, Z) in which the main reflector and subreflector are finally expressed. Note that in the four antenna arrangements we are proposing, $O_{MR} \equiv O_{SR} \equiv O$.

As for the classical Cassegrain and Gregorian systems [5], we are dealing with a system of eight parameters defining the overall geometry of the antenna, namely: D_m, F, D_s, θ_e, L_m, L_s, a, and f, where (see Figures 1 to 6):

D_m: diameter of the main parabolic reflector

F: focal distance of the main reflector

D_s: diameter of the subreflector (elliptical or hyperbolic)

θ_e: angle between the Z axis and the ray emanating from the focus, F_0, of the antenna in the direction of the subreflector edge

L_m: distance between the focus, F_0, of the antenna and the projection of the bottom-edge of the half-main-reflector onto the Z axis

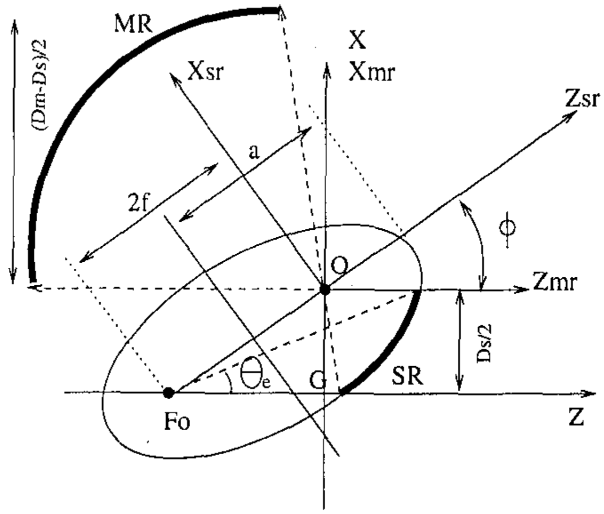

Figure 2a. A cross-sectional view of the elliptical-subreflector coordinate system with its parameters.

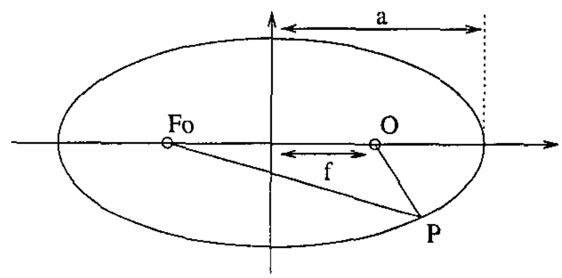

Figure 2b. The distance relationship in an ellipse.

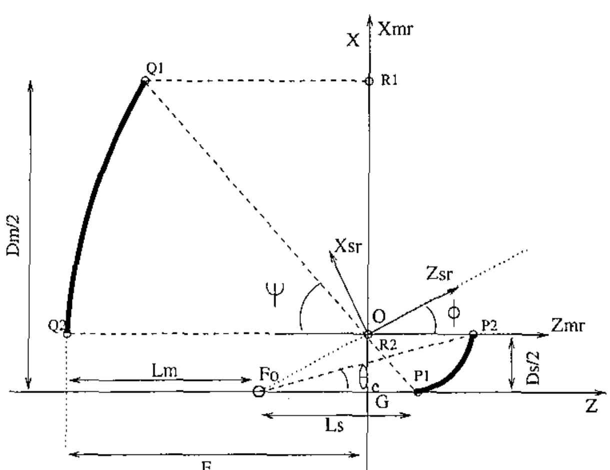

Figure 1. A cross-sectional view of a single-offset Gregorian displaced-axis dual-reflector antenna.

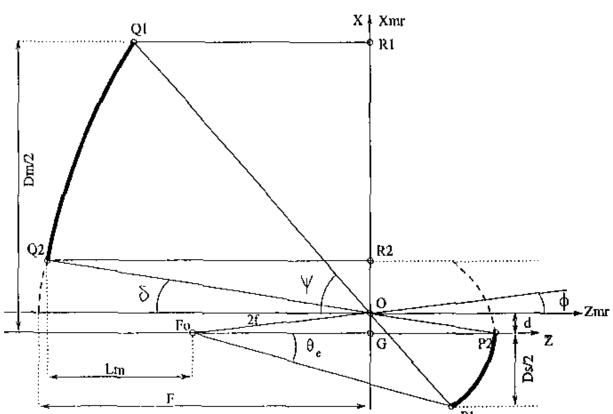

Figure 3. A cross-sectional view of a double-offset Gregorian displaced-axis dual-reflector antenna.

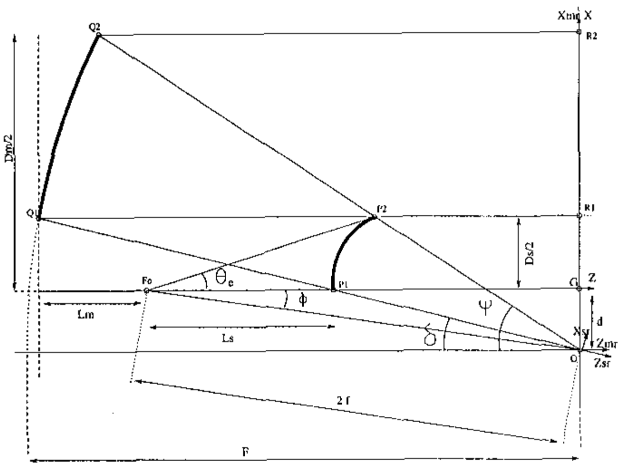

Figure 4. A cross-sectional view of a single-offset Cassegrain displaced-axis dual-reflector antenna.

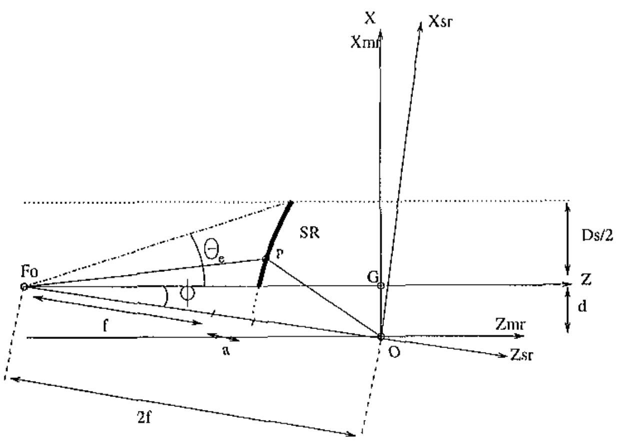

Figure 5. A cross-sectional view of the hyperbolic-subreflector coordinate system with its parameters.

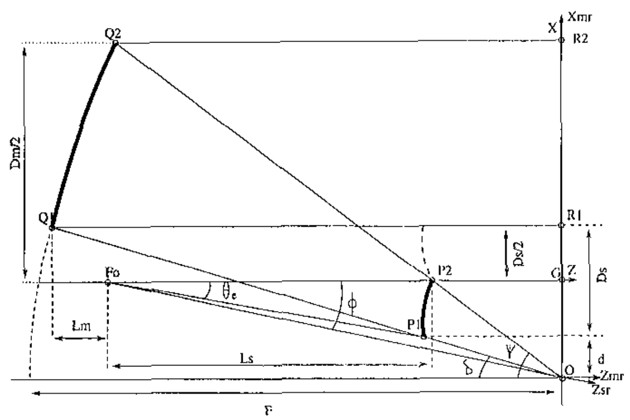

Figure 6. A cross-sectional view of a double-offset Cassegrain displaced-axis dual-reflector antenna.

L_s: distance between the focus, F_0, of the antenna and the apex of the subreflector

a and f: parameters defining the geometry of the subreflector

These parameters, however, cannot be specified arbitrarily. We choose four input parameters to define the antenna, namely, D_m, F, D_s and θ_e, and then calculate from these the other design parameters in closed form.

Other intermediate geometric parameters, used in finding the remaining four parameters (L_m, L_s, a and f) and defining the dual-reflector geometry, are:

ϕ: offset angle between the main-reflector coordinate system and the subreflector coordinate system (the angle between (O, Z_{MR}) and (O, Z_{SR}))

ψ: angle from the axis of the main reflector to the top edge of the main reflector in the main-reflector coordinate system

δ: angle from the axis of the main reflector to the bottom edge of the main reflector in the main-reflector coordinate system

d: offset parameter for designing the antennas for Options 2, 3, and 4.

For the definition of the main-reflector geometry, we consider only the upper part of the (O, X_{MR}, Z_{MR}) plane. The main-reflector profile, $z_{mr}(x_{mr})$, depends on the real parameter F, and is of the form

$$z_{mr}(x_{mr}) = \frac{(x_{mr})^2}{4F} - F, \tag{1}$$

with

$$0 \le x_{mr} \le \frac{D_m - D_s}{2}, \qquad \text{(Option 1)}$$

$$\frac{D_s - 2d}{2} \le x_{mr} \le \frac{D_m - 2d}{2}, \qquad \text{(Option 2)}$$

$$\frac{D_s + 2d}{2} \le x_{mr} \le \frac{D_m + 2d}{2}, \qquad \text{(Option 3)}$$

$$D_s + d \le x_{mr} \le \frac{D_m + D_s + 2d}{2}. \qquad \text{(Option 4)}$$

The subreflector profile, $z_{sr}(x_{sr})$, is defined in the (O, X_{SR}, Z_{SR}) plane, and depends on the two real parameters a and f. It is of the form

$$z_{sr}(x_{sr}) = a\sqrt{1 + \frac{(x_{sr})^2}{f^2 - a^2}} - f. \tag{2}$$

We have three possibilities:

- $0 < a < f$: In this case, z_{sr} represents a hyperboloid with axis of symmetry about the Z_{SR} axis, and with a focus at the origin of coordinates. The parameter f is half the distance between the focus and its image, and a is half the distance between the hyperboloid and its image, measured along the Z_{SR} axis. The eccentricity is $e = \frac{f}{a}$.

- $a > f > 0$: In this case, z_{sr} represents an ellipsoid with axis of symmetry about the Z_{SR} axis, and with one focus at the origin of coordinates. The parameter f is half the distance between the foci, and a is half the major axis of the ellipse. The eccentricity is $e = \frac{f}{a}$.
- $a = 0$: In this case, z_{sr} represents a plane parallel to the (X_{SR}, Y_{SR}) plane, with all z_{sr} coordinates equal to $-f$.

The points defining the subreflector are such that when x_{sr} is expressed in the main-reflector coordinate system,

$$-\frac{D_s}{2} \le [x_{sr}]_{\text{Expressed in the MR coordinate system}} \le 0 \quad \text{(Option 1)}$$

$$-\frac{D_s + 2d}{2} \le [x_{sr}]_{\text{Expressed in the MR coordinate system}} \le -d \quad \text{(Option 2)}$$

$$d \le [x_{sr}]_{\text{Expressed in the MR coordinate system}} \le \frac{D_s + 2d}{2} \quad \text{(Options 3 and 4)}$$

It is then easy to express the subreflector in the main-reflector coordinate system using the angle ϕ, and to then express both main reflector and subreflector in the antenna-coordinate system (G, X, Y, Z). The only task remaining is to consider the antenna to have a circularly-symmetric shape, i.e., to rotate the geometry around the (G, Z) axis.

4. Properties of displaced-axis dual-reflector antennas

In these arrangements, the main reflector will have a focal ring instead of a focal point. The subreflector will also have a focal ring, with one focus located at the focal ring of the main reflector, and the other at the focus of the antenna (the phase center of the feed).

Because of the displaced-axis geometry, there is no blockage by the subreflector, and this property also improves the feed mismatch caused by the reflections from the subreflector. It also permits the use of a smaller subreflector in close proximity to the feed, reducing rear radiation because of the small F/D_m ratio [2].

In designing the antennas, we are using three main properties of Cassegrain/Gregorian systems:

- For each system, the path length is the same for any ray from the focus, F_0, to the aperture, i.e., using the extreme rays, we have (see Figures 1, 3, 4 and 6):

$$\|F_0P_1\| + \|P_1Q_1\| + \|Q_1R_1\| = \|F_0P_2\| + \|P_2Q_2\| + \|Q_2R_2\| \qquad (3)$$

- The distance relationship in an ellipse gives [6] (see Figures 2a and 2b):

$$\|F_0P\| + \|OP\| = 2a$$

- The distance relationship in a hyperboloid gives [6] (see Figure 5):

$$\|F_0P\| - \|OP\| = 2a$$

5. Displaced-axis Gregorian antennas

5.1 Option 1: Single-offset Gregorian

Figure 1 shows the geometry of the antenna. To understand how this geometry has been derived, we start with the cross-section of a Gregorian dual-reflector antenna. The main reflector is parabolic, and the subreflector is a portion of an ellipse. The two foci of the subreflector are located at the focus of the main reflector and at the phase-center of the feed. In a Gregorian system, the rays emitted by the feed are inverted, so that the lower portion of the subreflector reflects the incident rays to the upper section of the main reflector.

Most of the work in this section is based on [1]. From the four input parameters (D_m, F, D_s, and θ_e), and using the fact that the path length is the same for any ray from the focus to the aperture, along with formulas related to paraboloid, hyperboloid, and ellipsoid [6], we find

$$L_m = \frac{FD_m}{D_m - D_s} - \frac{D_s}{4}\left[\frac{\cos(\theta_e)+1}{\sin(\theta_e)}\right], \qquad (4)$$

$$\tan(\phi) = \frac{2}{\frac{\cos(\theta_e)+1}{\sin(\theta_e)} - \frac{4F}{D_m - D_s}}, \qquad (5)$$

$$f = \frac{D_s}{4\sin(\phi)}, \qquad (6)$$

$$\tan(\psi) = \frac{8F(D_m - D_s)}{(D_m - D_s)^2 - 16F^2}, \qquad (7)$$

$$L_s = 2f\cos(\phi) + \frac{D_s}{2\tan(\psi)}, \qquad (8)$$

$$a = \frac{D_s}{8}\left[\frac{\cos(\theta_e)+1}{\sin(\theta_e)}\right] + \frac{FD_s}{2(D_m - D_s)}. \qquad (9)$$

We have now defined all the parameters necessary to represent the displaced-axis Gregorian single-offset dual-reflector antenna system (note that $d = 0$ and $\delta = 0$).

5.2 Option 2: Double-offset Gregorian

The geometry of such a system is shown in Figure 3, where a parabolic main reflector is used in conjunction with an elliptical

Table 1. Option 2: The coordinates of the points for the double-offset Gregorian system.

Point	x	z
Q_1	$\frac{D_m-2d}{2}$	$\frac{(D_m-2d)^2}{16F}-F$
Q_2	$\frac{D_s-2d}{2}$	$\frac{(D_s-2d)^2}{16F}-F$
P_1	$-\left(\frac{D_s+2d}{2}\right)$	$\frac{(D_s+2d)\left[\frac{(D_m-2d)^2}{16F}-F\right]}{D_m-2d}$
P_2	$-d$	$\frac{2d\left[\frac{(D_s-2d)^2}{16F}-F\right]}{D_s-2d}$
F_0	$-d$	$\frac{(D_s+2d)\left[\frac{(D_m-2d)^2}{16F}-F\right]}{D_m-2d}-\frac{D_s}{2\tan(\theta_e)}$
R_1	$\frac{D_m-2d}{2}$	0
R_2	$\frac{D_s-2d}{2}$	0

subreflector in a double-offset arrangement. The input parameters are again D_m, F, D_s, and θ_e, and we will express the remaining design parameters in terms of these input parameters.

The ray-tracing in this system (see Figure 3) is given by Equation (3). For this option, the coordinates of the points F_0, P_1, P_2, Q_1, Q_2, R_1, and R_2 in the (O, X_{MR}, Z_{MR}) coordinate system are given in Table 1. Using Equation (3) and the coordinates of the points in Table 1, we find a function, Γ, which depends only on the variable d (and uses D_m, D_s, F, and θ_e).

The first step of the design is then to solve the equation

$$\Gamma(d)=\|F_0P_1\|+\|P_1Q_1\|+\|Q_1R_1\|-\|F_0P_2\|-\|P_2Q_2\|-\|Q_2R_2\|=0 \tag{10}$$

with a simple solver, and to use the root, d, of Γ in the following relations (see Figure 3):

$$\tan(\psi)=\frac{8F(D_m-2d)}{16F^2-(D_m-2d)^2}, \tag{11}$$

$$L_s=\frac{D_s}{2\sin(\theta_e)}+\frac{D_s+2d}{2\sin(\psi)}-\frac{d\left[16F^2+(D_s-2d)^2\right]}{8F(D_s-2d)}, \tag{12}$$

$$L_m=F-\frac{(D_s-2d)^2}{16F}+\frac{16dF^2-d(D_s-2d)^2}{8F(D_s-2d)}-L_s, \tag{13}$$

$$a=\frac{D_s}{4\sin(\theta_e)}+\frac{D_s+2d}{4\sin(\psi)}, \tag{14}$$

$$\tan(\phi)=\frac{8dF(D_s-2d)}{8F(D_s-2d)L_s-16dF^2+d(D_s-2d)^2}, \tag{15}$$

$$f=\frac{d}{2\sin(\phi)}, \tag{16}$$

$$\tan(\delta)=\frac{8F(D_s-2d)}{16F^2-(D_s-2d)^2}. \tag{17}$$

We have now defined all the parameters necessary to represent the displaced-axis Gregorian double-offset dual-reflector antenna system.

6. Displaced-axis Cassegrain antennas

6.1. Option 3: Single-offset Cassegrain

The geometry of such a system is shown in Figure 4, where a parabolic main reflector is used in conjunction with a hyperbolic subreflector in a single-offset arrangement. The input parameters are again D_m, F, D_s, and θ_e, and we will express the remaining design parameters in terms of these input parameters.

For this option, the coordinates of the points F_0, P_1, P_2, Q_1, Q_2, R_1, and R_2 in the (O, X_{MR}, Z_{MR}) coordinate system are given in Table 2. From Equation (10) we can then define Γ, and use the root, d, of Γ in the following relations (see Figure 4):

$$\tan(\psi)=\frac{8F(D_m+2d)}{16F^2-(D_m+2d)^2}, \tag{18}$$

Table 2. Option 3: The coordinates of the points for the single-offset Cassegrain system.

Point	x	z
Q_1	$\frac{D_s+2d}{2}$	$\frac{(D_s+2d)^2}{16F}-F$
Q_2	$\frac{D_m+2d}{2}$	$\frac{(D_m+2d)^2}{16F}-F$
P_1	d	$\frac{2d\left[\frac{(D_s+2d)^2}{16F}-F\right]}{D_s+2d}$
P_2	$\frac{D_s+2d}{2}$	$\frac{(D_s+2d)\left[\frac{(D_m+2d)^2}{16F}-F\right]}{D_m+2d}$
F_0	d	$\frac{(D_s+2d)\left[\frac{(D_m+2d)^2}{16F}-F\right]}{D_m+2d}-\frac{D_s}{2\tan(\theta_e)}$
R_1	$\frac{D_s+2d}{2}$	0
R_2	$\frac{D_m+2d}{2}$	0

Table 3. Option 4: The coordinates of the points for the double-offset Cassegrain system.

Point	x	z
Q_1	$D_s + d$	$\frac{(D_s+d)^2}{4F} - F$
Q_2	$\frac{D_m + D_s + 2}{2}$	$\frac{(D_m + D_s + 2d)^2}{16F} - F$
P_1	d	$\frac{d\left[\frac{(D_s+d)^2}{4F} - F\right]}{D_s + d}$
P_2	$\frac{D_s + 2d}{2}$	$\frac{(D_s+2d)\left[\frac{(D_m+D_s+2d)^2}{16F} - F\right]}{D_m + D_s + 2d}$
F_0	$\frac{D_s + 2d}{2}$	$\frac{d\left[\frac{(D_s+d)^2}{4F} - F\right]}{D_s + d} - \frac{D_s}{2\tan(\theta_e)}$
R_1	$D_s + d$	0
R_2	$\frac{D_m + D_s + 2}{2}$	0

$$L_s = \frac{D_s}{2\ \sin(\theta_e)} + \frac{D_m - D_s}{2\ \sin(\psi)} + \frac{(D_s+2d)^2 - (D_m+2d)^2}{16F} - \frac{16F^2 D_s + D_s(D_s+2d)^2}{16F(D_s+2d)}, \quad (19)$$

$$a = \frac{L_s}{2} - \frac{d\left[16F^2 + (D_s+2d)^2\right]}{16F(D_s+2d)}, \quad (20)$$

$$\tan(\delta) = \frac{8F(D_s+2d)}{16F^2 - (D_s+2d)^2}, \quad (21)$$

$$L_m = \frac{16F^2 - (D_s+2d)^2}{16F} - L_s + (2a - L_s)\cos(\delta), \quad (22)$$

$$\tan(\phi) = -\frac{d}{L_s + (L_s - 2a)\cos(\delta)} \ \text{(note that } \phi \le 0\text{)}, \quad (23)$$

$$f = \frac{L_s + (L_s - 2a)\cos(\delta)}{2\cos(\phi)}. \quad (24)$$

We have now defined all the parameters necessary to represent the displaced-axis Cassegrain single-offset dual-reflector antenna system.

6.2. Option 4: Double-offset Cassegrain

The geometry of such a system is shown in Figure 6, where a parabolic main reflector is used in conjunction with a hyperbolic subreflector in a double-offset arrangement. The input parameters

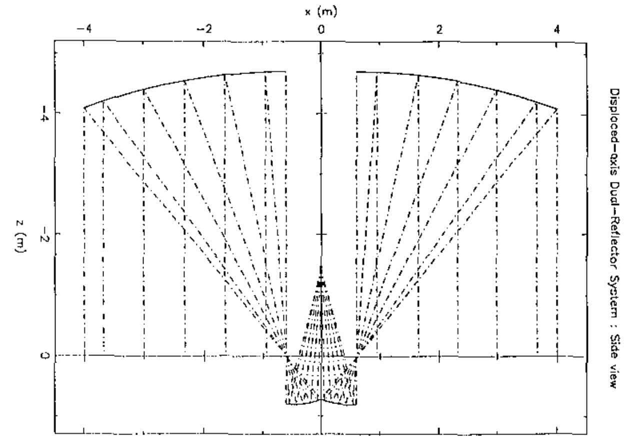

Figure 7. The antenna geometry of option 1: $D_m = 8\,\text{m}$, $F = 4.7\,\text{m}$, $L_m = 3.2506\,\text{m}$, $D_s = 1.2\,\text{m}$, $L_s = 2.1702\,\text{m}$, $d = 0\,\text{m}$, $a = 1.554\,\text{m}$, $f = 0.7843\,\text{m}$, $\theta_e = 15°$.

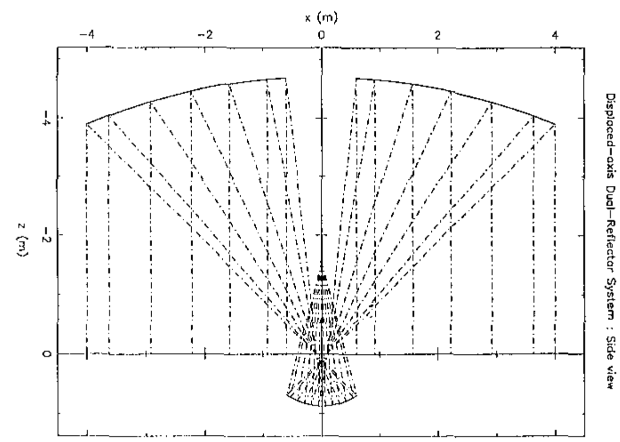

Figure 8. The antenna geometry of option 2: $D_m = 8\,\text{m}$, $F = 4.7\,\text{m}$, $L_m = 3.1382\,\text{m}$, $D_s = 1.2\,\text{m}$, $L_s = 2.4204\,\text{m}$, $d = 0.0941\,\text{m}$, $a = 1.6488\,\text{m}$, $f = 0.7755\,\text{m}$, $\theta_e = 15°$.

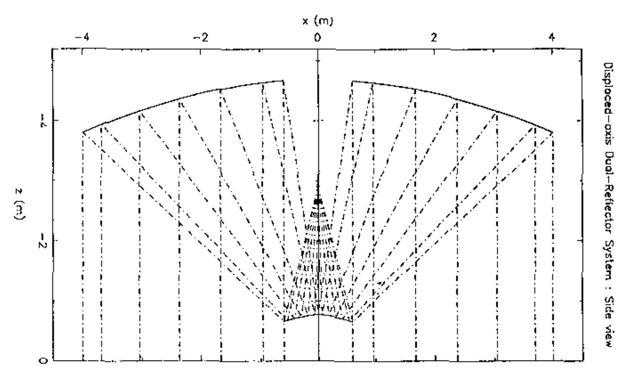

Figure 9. The antenna geometry of option 3: $D_m = 8\,\text{m}$, $F = 4.7\,\text{m}$, $L_m = 1.7698\,\text{m}$, $D_s = 1.2\,\text{m}$, $L_s = 2.1256\,\text{m}$, $d = 0.1196\,\text{m}$, $a = 0.6697\,\text{m}$, $f = 1.4525\,\text{m}$, $\theta_e = 15°$.

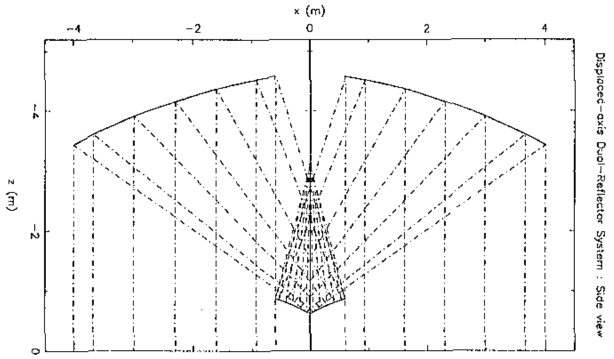

Figure 10. The antenna geometry of option 4: $D_m = 8\,\mathrm{m}$, $F = 4.7\,\mathrm{m}$, $L_m = 1.4802\,\mathrm{m}$, $D_s = 1.2\,\mathrm{m}$, $L_s = 2.4848\,\mathrm{m}$, $d = 0.2787\,\mathrm{m}$, $a = .7051\,\mathrm{m}$, $f = 1.6127\,\mathrm{m}$, $\theta_e = 15°$.

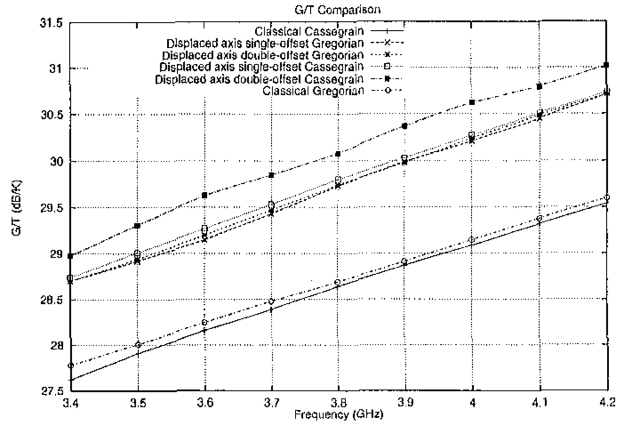

Figure 11. The G/T comparison.

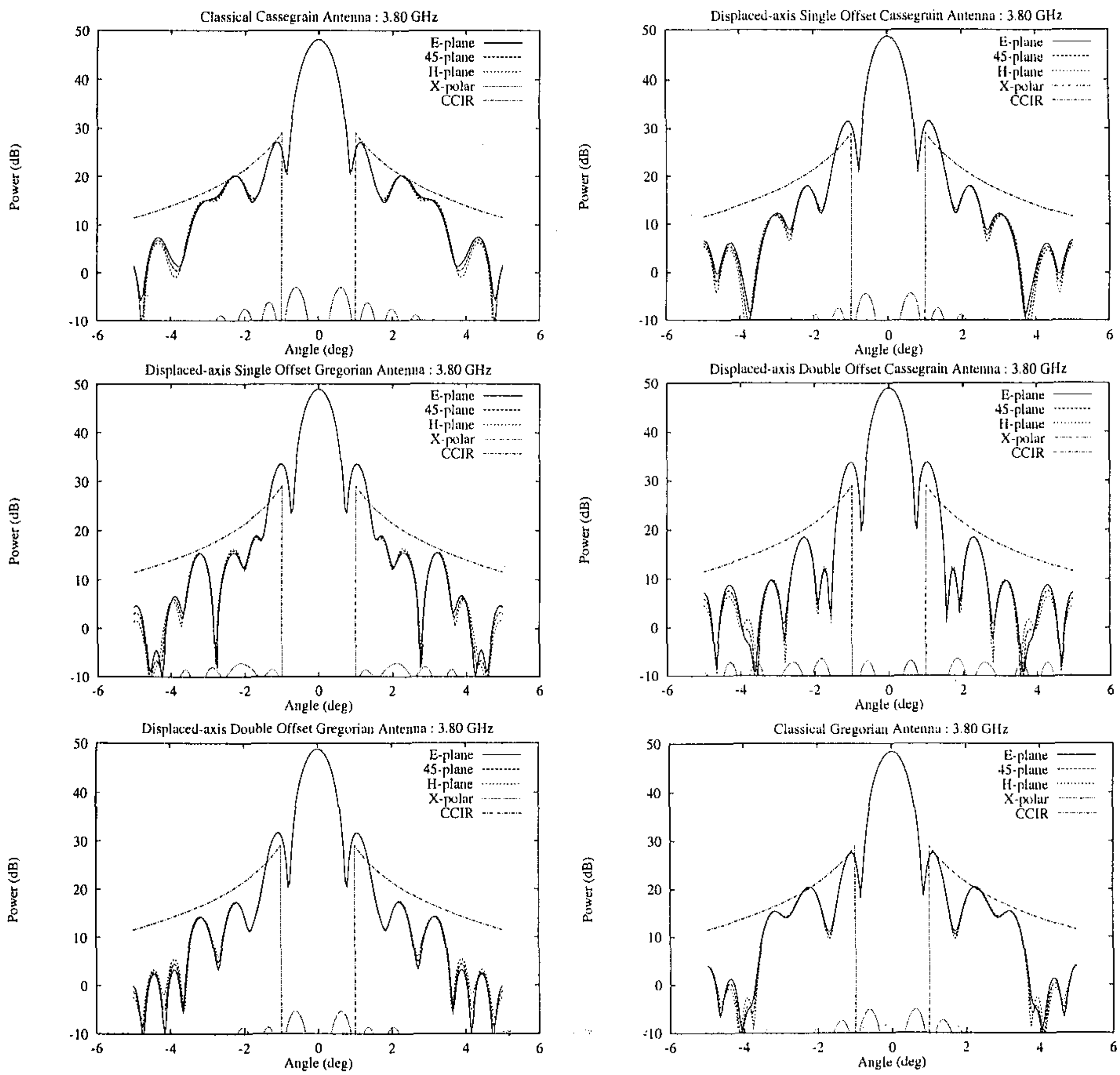

Figure 12. The radiation patterns at 3.80 GHz.

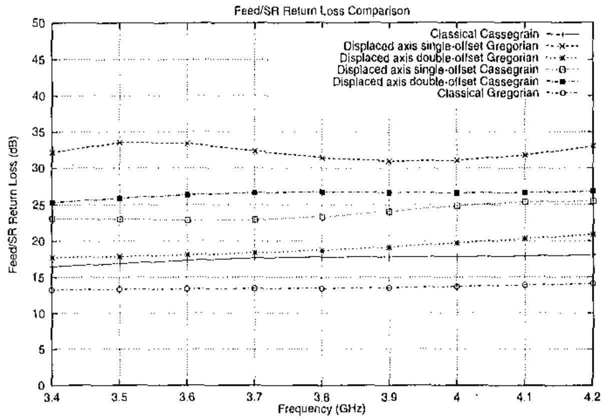

Figure 13. The feed/subreflector return loss.

are again D_m, F, D_s, and θ_e, and we will express the remaining design parameters in terms of these input parameters.

For this option, the coordinates of the points F_0, P_1, P_2, Q_1, Q_2, R_1, and R_2 in the (O, X_{MR}, Z_{MR}) coordinate system are given in Table 3. From Equation (10), we can then define Γ, and use the root, d, of Γ in the following relations (see Figure 6):

$$\tan(\psi) = \frac{8F(D_m + D_s + 2d)}{16F^2 - (D_m + D_s + 2d)^2}, \tag{25}$$

$$L_s = \frac{D_s}{2\sin(\theta_e)} + \frac{D_s\left[4F^2 + (D_s + 2d)^2\right]}{4F(D_s + d)} \cdot \\ - \frac{(D_s + d)^2}{4F} - \frac{D_m}{2\sin(\psi)} + \frac{(D_m + D_s + 2d)^2}{16F}, \tag{26}$$

$$a = \frac{D_s}{4\sin(\theta_e)} - \frac{d\left[4F^2 + (D_s + d)^2\right]}{8F(D_s + d)}, \tag{27}$$

$$\tan(\delta) = \frac{4F(D_s + d)}{4F^2 - (D_s + d)^2}, \tag{28}$$

$$L_m = F - \frac{(D_s + d)^2}{4\ F} - L_s \\ - \left[F - \frac{D_m}{2\sin(\psi)} + \frac{(D_m + D_s + 2d)^2}{16F}\right]\cos(\psi), \tag{29}$$

$$\tan(\phi) = -\frac{2F(D_s + 2d)}{4F^2 - (D_s + d)^2 - 4FL_m} \quad \text{(note that } \phi \le 0\text{)}, \tag{30}$$

$$f = \frac{4F^2 - (D_s + d)^2 - 4FL_m}{8F\cos(\phi)}. \tag{31}$$

We have now defined all the parameters necessary to represent the displaced-axis Cassegrain double-offset dual-reflector antenna system.

7. Examples

Examples of dual-reflector antennas, designed using the different options, are presented in Figures 7 to 10 for Options 1 to 4. These four antennas have been designed using the same input parameters, i.e., $D_m = 8$ m, $F = 4.7$ m, $D_s = 1.2$ m, and $\theta_e = 15°$. These four antennas have been analyzed over the 3.4-4.2 GHz band, and compared with equivalent classical Cassegrain and Gregorian systems in terms of G/T (see Figure 11), radiation pattern (see Figure 12), and feed/subreflector return loss (see Figure 13). The main conclusion of this brief analysis (using Physical Optics on both reflectors, and assuming a theoretical Gaussian feed) is that displaced-axis systems offer better G/T and feed/subreflector return-loss performance. On the other hand, the radiation pattern first sidelobe for the four designs considered is higher than for the equivalent classical Cassegrain or Gregorian systems.

8. Conclusions

An easy procedure has been presented for the design in Geometrical Optics of displaced-axis dual-reflector antennas. Four options are available to the antenna designer. The main advantage of these antennas is that there is no blockage (from the Geometrical Optics point of view) by the subreflector, and no or very little energy is radiated back to the feed aperture by the subreflector. These antennas can be very useful for designing small antennas (in terms of wavelength), where the lack of subreflector-blockage can be a prime consideration.

9. References

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